

The Formation Timescales of Giant Spheroids

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Abstract. We review current progress in the study of the stellar populations of early-type galaxies, both locally and at intermediate redshifts. In particular, we focus on the ages of these galaxies and their evolution in hopes of determining the star formation epochs of their stars. Due to serious remaining systematic uncertainties, we are unable to constrain these epochs precisely. We discuss our results on the evolution of stellar populations in the context of other observables, in particular the evolution of the Fundamental Plane of early-type galaxies.

1. Introduction

The sequence and timescales of galaxy formation are a major issue in astrophysics today. The formation histories of early-type galaxies, ellipticals and S0's, though seemingly simple systems, remain a puzzle. Long thought to be very old, homogeneous, coeval systems varying only in their metallicities (Baade 1962; Faber 1977; Burstein 1977), accumulating observational evidence on stellar populations of ellipticals and S0's have challenged this view. A number of field elliptical galaxies clearly have had significant recent star formation (see below), and many early-type galaxies have evidence for recent dynamical disturbances (Schweizer & Seitzer 1992). Theoretically, models of the commonly accepted mode of galaxy formation—hierarchical clustering (e.g. Blumenthal et al. 1984; Kauffmann, White, & Guiderdoni 1993)—suggest that merging, accretion, and star formation have continued in the giant early-type galaxy population up until the current epoch, at least in some galaxies in low-density environments. However, these models are unconstrained by detailed observations of the formation epoch (parameterized by the formation redshift z_f of the dominant stellar population) and the timescale of star formation in early-type galaxies.

Detailed studies of the stellar populations of early-type galaxies allow us to determine or at least infer these timescales. In particular, ages derived from

stellar populations and their evolution with redshift allow us to determine *when* the stars in giant spheroids form, and their nucleosynthetic properties (their metallicities and relative abundances such as $[\alpha/\text{Fe}]$) allow us to determine *how long* the star formation event(s) lasted.

Unfortunately, such detailed data are difficult to gather due to the *age-metallicity degeneracy* (e.g., O’Connell 1986; Worthey 1994; Trager 1999), which plagues all stellar population studies at some level. As stellar populations age, the populations get cooler and thus redder. Unfortunately, stellar populations also get cooler and redder with increasing metallicity. Colors and metal absorption lines like Mg_2 are therefore degenerate to compensating changes in age and metallicity. Worthey (1994, following earlier work by O’Connell 1980, Rabin 1982, Burstein et al. 1984, and Rose 1985) showed that the Balmer lines of hydrogen can break this age-metallicity degeneracy. These absorption lines originate in the hot main-sequence turnoff (MSTO) stars, and the MSTO temperature is much more sensitive to age than to metallicity in stellar populations (cf. Fig. 1 of Trager 1999). However, because even the Balmer lines are still somewhat sensitive to metallicity, a combination of Balmer and metal lines are used to determine ages and abundances of early-type galaxies (Figs. 1 and 2; e.g., González 1993; Worthey 1994; Jørgensen 1997, 1999, this meeting; Kuntschner 2000; Trager et al. 2000a,b).

In this contribution, we summarize the current state of our own studies of the stellar populations of both local and distant early-type galaxies. We focus on our attempts to determine the typical formation redshifts of these galaxies in various environments and on the difficulties in measuring—and comparing—the stellar populations of early-type galaxies.

Throughout this contribution, we use the stellar population models of Worthey (1994) for consistency with earlier work, but note that the absolute time-scale of these models (that is, MSTO temperature at fixed age) is suspect, with the oldest models being too old by about 25–35% when compared with models based on recent isochrones by the Padova group (e.g., Girardi et al. 2000; cf. Charlot, Worthey & Bressan 1996). However, the *relative* ages of galaxies are nearly unaffected by the choice of stellar population model (Trager et al. 2000a), which are the data of interest here. Also, it is helpful to keep in mind that the ages (and abundances) presented here are those of single-burst, single-metallicity stellar populations (SSPs); see Trager et al. (2000b) for details of the effects of composite populations on SSP parameters.

2. The Stellar Populations of Nearby Early-Type Galaxies

At the present, only a limited number of early-type galaxies (less than 100 total ellipticals and S0’s) have had absorption line strengths measured accurately enough for detailed stellar population work (that is, $\sigma_{H\beta} < 0.05 \text{ \AA}$, or $\text{S/N} > 75\text{\AA}$). Many of these galaxies are shown in Figure 1, in which the galaxies are separated by morphology (elliptical vs. S0) and by environment (cluster vs. field). A full analysis of the stellar populations of the field and Fornax Cluster ellipticals is given by Trager et al. (2000b), but the salient points for a discussion of the formation epochs of early-type galaxies can be gleaned directly from this figure.

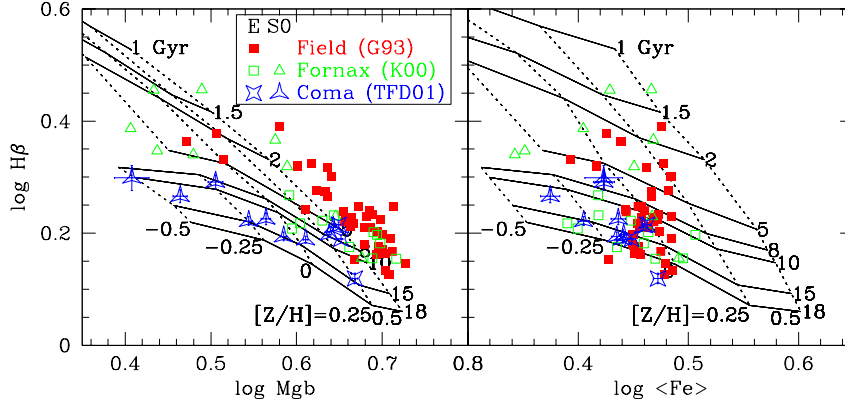


Figure 1. The line strengths of local early-type galaxies, by morphology and environment. Squares are ellipticals, triangles are S0's, solid points are “field” (isolated, group, and Virgo cluster) galaxies from González (1993), open points are Fornax Cluster galaxies from Kuntschner (2000), and stellated points are Coma Cluster galaxies (Trager et al., in prep.). Note the large dispersion in the $H\beta$ strengths—and thus ages—of field ellipticals and Fornax S0's but the rather tight distribution in the $H\beta$ strengths of Fornax ellipticals and Coma galaxies, both ellipticals and S0's.

Field ellipticals. Field ellipticals from González (1993), which include ellipticals in environments ranging from isolated galaxies to Virgo Cluster galaxies, show a wide spread in age. This spread in age should not be interpreted necessarily as indicative of a wide range of formation redshifts for the entire stellar populations of these object. Indeed, Trager et al. (2000b) have interpreted this spread in the context of two-burst models of star formation: Small “frostings” of recent star formation occur on top of massive old stellar populations, with the range in inferred ages corresponding to some combination of the time at which these frostings were formed and the strength of the burst.

Cluster ellipticals. Cluster ellipticals in Virgo (González 1993; Trager et al. 2000b), Fornax (Kuntschner 2000), and in the core of Coma (Trager, Faber, & Dressler, in prep.) appear to be coeval to within a few Gyr, with virtually no recent star formation, except in a few Virgo galaxies. This lack of detectable recent star formation is in agreement with color-magnitude studies of early-type cluster galaxies (e.g., Bower, Lucey, & Ellis 1992).

Cluster S0's. Any distinction between field and cluster S0's is less clearly defined than for ellipticals. The stellar populations of Fornax S0's (Kuntschner 2000) certainly span a large range in age (similar to the stellar populations of field S0's; Fisher, Franx, & Illingworth 1996), but those in the core of Coma (Trager et al., in prep.) appear to have a rather tight age distribution, similar to the cluster ellipticals. A detection of any possible

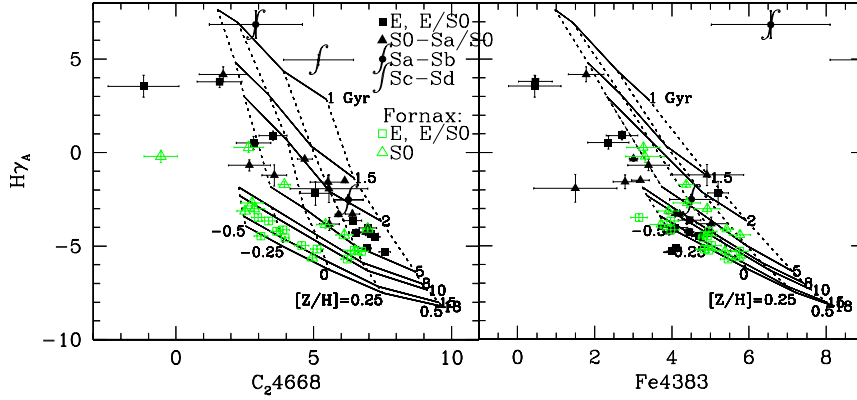


Figure 2. The evolution of the absorption line strengths of cluster galaxies. Galaxies are coded by redshift (open points are Fornax Cluster galaxies at $z \approx 0$; solid points are galaxies in Abell 851 at $z = 0.41$) and morphology (squares are ellipticals and E/S0 transition cases; triangles are S0's, S0/Sa, and Sa/S0 transition cases; later-type galaxies are integral signs). Evolution is detected at the 5σ level in the $H\beta$ strengths of early-type cluster galaxies, modulo uncertainties in the corrections needed to bring the Fornax galaxies to the same very large physical apertures as the distant galaxies and line strength system calibrations in the distant galaxies (see text).

environmental effect in the stellar populations of local S0's will require a much larger database of high-quality spectra than is currently available.

3. The Evolution of the Stellar Populations of Cluster Galaxies

The lack of detectable recent star formation in the majority of cluster ellipticals suggests that such galaxies can be used as direct tracers of the evolution of the oldest stellar populations. In this section, we present the first results of our ongoing study of the evolution of the stellar populations of cluster galaxies (Trager 1997; Trager, Faber, & Dressler, in prep.).

Many techniques are available to detect and characterize the evolution of early-type galaxies. Here we concentrate on two methods: direct detection of the evolution of stellar population ages and the evolution of line strength–velocity dispersion relations. (Other methods, such as the evolution of cluster color–magnitude diagrams and the evolution of the morphology–density relation, are described elsewhere; see, e.g., Lubin, this volume). We compare these two methods with the evolution of the Fundamental Plane of early-type galaxies in the next section.

We begin with the most ambitious method, direct detection of the evolution of stellar populations ages of early-type galaxies. Figure 2 shows our first attempt: a comparison of line strengths of early-type galaxies in Abell 851

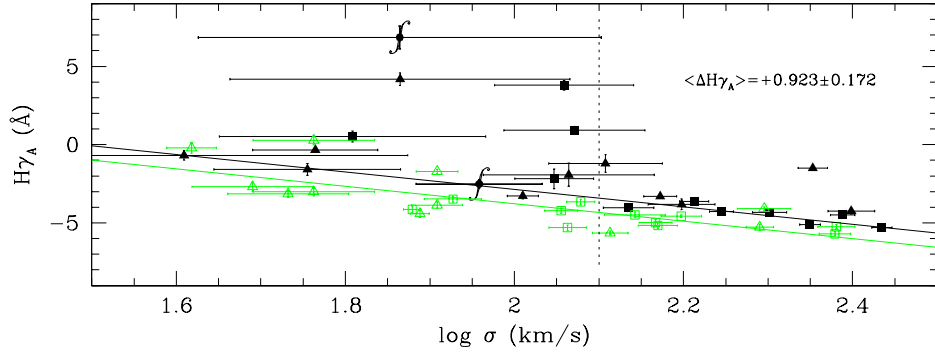


Figure 3. The evolution of the Balmer line-velocity dispersion relation (cf. Kelson et al. 2001). Assuming all the evolution in $H\gamma_A$ is due to age, galaxies at $z \approx 0.4$ are 70% the age of Fornax galaxies of the same velocity dispersion (for typical stellar population models).

(=CL0939+4713), a rich cluster at $z = 0.406$, to those in Fornax. Focussing first on the elliptical galaxies (squares), the ellipticals in Abell 851 are about 40% the age of the Fornax ellipticals ($> 5\sigma$ significance). However, this result is subject to three major uncertainties. (1) The distant galaxies are not necessarily on the same line strength system as the local galaxies; in particular, the C_24668 line strengths may be systematically uncertain by up to 0.25 \AA , and there may be overall calibration issues with the poorly understood $H\gamma_A$ index. (2) The model line strengths of $H\gamma_A$ appear to be too weak by about 1 \AA on comparison with stellar population parameters derived from $H\beta$ for Fornax galaxies. This offset appears to be due to uncertainties in the empirically-determined fitting functions (Worthey & Ottaviani 1997). While this offset has been corrected in Fig. 2, its exact magnitude is still uncertain. (3) Because all early-type galaxies have gradients in their line strengths (e.g., Davies, Sadler, & Peletier 1993), galaxies must be measured through the same physical aperture in order to directly compare their line strengths and thus their stellar populations. Unfortunately, the extraction aperture used for the distant galaxies ($1'' \times 2''.4$) projects to a very large aperture on the Fornax galaxies ($\sim 1' \times 2'$), much larger than the apertures through which accurate line strengths for local galaxies have been measured (a result anticipated by Kennicutt 1992). We are therefore forced to apply to the rather uncertain gradients of early-type galaxies to generate aperture corrections for the *local* galaxies. This is currently our largest uncertainty; high S/N, raster-scanned spectroscopy of local early-type galaxies (cf. Kennicutt 1992) will be required to resolve this issue.

Another method is to use the evolution of line strength-velocity dispersion relations. Although the pioneering work of Bender, Ziegler, & Bruzual (1996) used the Mg b- σ relation, using more age-sensitive indices like the high-order Balmer lines (Kelson et al. 2001) provides much better leverage on the evolution. Figure 3 shows the evolution of the $H\gamma_A$ - σ relation from $z = 0.41$ (Abell 851) to $z \approx 0$ (Fornax). Assuming that the evolution is *entirely due to age evolution at*

fixed velocity dispersion—and not due to metallicity differences between cluster galaxies of the same velocity dispersion in the two clusters, to changes in the *slope* of the relation (if, say, the lower-mass galaxies are younger than the older galaxies; cf. Trager et al. 2000b), or some other manifestation of the age-metallicity degeneracy—then the galaxies in Abell 851 are 70% the age of the Fornax galaxies at fixed velocity dispersion using common stellar population models. This result has the same systematic uncertainties as the previous method—aperture corrections, line strength calibrations, and model uncertainties—and moreover, since only a single absorption line is used, the age-metallicity degeneracy can play a significant role.

4. Discussion and Conclusions

We summarize the results from these methods and the evolution of the Fundamental Plane (van Dokkum & Franx 2001; Trager et al. in prep.) in Figure 4; at the moment, these three methods are marginally inconsistent. We have tried to point out the various difficulties involved in measuring these evolutionary indicators: the line strengths required extremely high signal-to-noise and therefore efficient spectrographs on large telescopes, and systematic uncertainties may be large. Systematic uncertainties aside, another effect may be present. Small amounts of recent star formation can strengthen the Balmer lines far out of proportion to the actual mass involved in the burst (Trager et al. 2000b). A recent study of NUV-optical colors of galaxies in Abell 851 (Ferreras & Silk 2000) suggests that such recent star formation may have occurred in many of these objects. This might explain the enhanced $H\gamma_A$ strengths of the distant galaxies without constraints from the evolution of the Fundamental Plane of early-type galaxies (e.g., van Dokkum & Franx 2001), but this explanation appears to be inconsistent with the evolution of the $H\gamma_A$ - σ relation.

In conclusion, we have *directly detected evolution* in the stellar populations of early-type cluster galaxies out to a redshift of $z = 0.41$. However, due to systematic uncertainties in measuring and comparing absorption line strengths, the exact amount of the evolution and the significance of this result is still unknown. Formation redshifts of $1 \lesssim z_f \lesssim 5$ are consistent with the current data (Fig. 4), but a more precise answer awaits better calibration of both the distant *and* local data.

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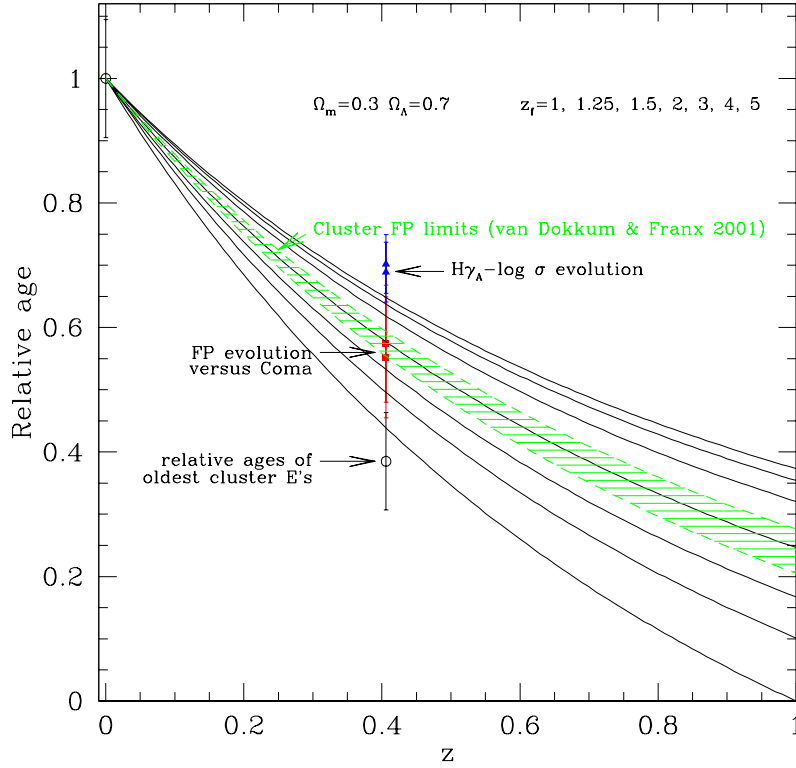


Figure 4. Constraints on the formation redshift of early-type cluster galaxies from three stellar population evolutionary indicators. The open circle represents the limits from the relative ages of the oldest cluster ellipticals in Fornax ($z = 0$) and Abell 851 ($z = 0.41$) from Fig. 2; the solid triangles represent the limits from the evolution of the $H\gamma_A - \sigma$ relation from Fornax to Abell 851 from Fig. 3 (two different stellar population models); and the solid squares represent the evolution of the Fundamental Plane from Coma to Abell 851 (photometry from Ziegler et al. 1999; authors' own velocity dispersions). The solid lines represent passively evolving stellar populations with formation redshifts $z_f = 1, 1.25, 1.5, 2, 3, 4, 5$, from bottom to top. The hatched region is the best fit from the evolution of the FP from $z \approx 0$ to $z = 0.83$, including a correction based model of morphological transformations onto the FP (van Dokkum & Franx 2001). Due to uncertainties in aperture corrections and line strength system calibrations in Figs. 2 and 3 and the age-metallicity degeneracy in Figs. 3 and 4, the formation redshift of early-type cluster galaxies is still ill-constrained, although $1 \lesssim z_f \lesssim 5$ is certainly reasonable, with $z_f \approx 2$ preferred by the FP studies.

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